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A New Approach for Exploring Ice Sheets and Sub-Ice Geology

important part of geophysical traverses i the Antarctic in a sheet as lar back as the hese memoris lost their leading role for are thickness measurements to mich laster ground-based and airborne radat sur-veys because of the considerable logistical effort miscessary for seismic data acquisition thowever, new actievements with a vibrator source in active seismics (vibroseis for short) could open new prospects and loster future geological and glaciological surveys in Ant-nictica and Greenland and on ice caps and glaciers

ctive seismic methods have the upique ability to image solvier geology and dy obtain its physical properties. For nor at the basat interface of an ice sheet plays a prematicile in controlling ice dynamics and is targely determined by the presence of water and/or sediments underpeatly the ice. High-quality seismic reflection measures ments came in demand as scientific inter est in the dynamics of ice streams to g. West Adiancia, ice streams) increased and as site surveys were needed for optimizer sampling of sub-ice sediments for pateochmate studies te a. Lane Roberts Project. Antarctic Geoogical Drilling (ANDRILL). Nevertheless the available literature demonstrates that seismoc studies on for sheets are not with spread and are only carried out on small. local scales over a lew tens of kilometers. Prominent examples of such seismic studie in the observation of transient processes in bert geology driven by ice flow [Smith et al., 2007] and the long record of seismic exploration of subglacial lake environments for example, around Lake Vostok and more recently around substance Lake Elsworth. Seisode projectics of the ice sheets remain only an occasional lope. [Hogan et al., 2008] often complementary to radar

The Fire-Lanes Postdem

The appertons of meters of an accestnet consist of a highly points layer of him isnow that is more than 1 year old), which acts as all acoustic waveguide, or trap, making the excitation of seismic waves from a sur-face source difficult. Soft fun causes large lace source utilical. Soft from causes large inelastic energy bases for impulsive sources. Dering most seismic surveys in Antarctica, researchers have used explorers in 10 to 20 mater deep from those for overcome signal attenuation caused by the steep velocity gar-dient in the softace laper between saft from and harder ice. The boreholds are diided by different techniques, requiting consider able functiond energy for each hole. With the seismic source below the surface, sur-face ghost reflections are commonly pos-em in the data. Despite mose direculties explosives sources in shallow borgholes are still the simplest way to obtain acceptable

data quality. Even with this approach, involving mirumal efforts, the recessary ingistical requirements have discouraged the acquisition of longer seismic profites, for example as part of overland fraverses.

The Villiamors Surhing Sounce

During the 2009-2000 Antarctic held sea othe Lanking Micros-Physical Properties to Macro Features in her Sheets With Deophysical Techniques (LIMPR'S) project aimed to make seismic vibrator measurements for the hist time in Antarctica (Koshillersen et al. 200] In contrast to an inpulsive surface source of millisecond duration, a controlled vibrator source emits energy as a binte amplitude pressure pulse over many secunds. Energy losses by metastic behavior are thus much less because of reduced ground

The project used a track-mounted Failing Y-1000 elbeator i peak actuator force equivifeut to 12 foose on skis towed by a Pisten-Bully stowent on the floating Ekström Ice Shell ocar the German research station Neu-roayer III. Sweeps of 10-second duration. with a linear increase in bequeries over the range of 10-100 herry were compared to shots of 300-grant explosive charge fixed in Hemeter-deep frorefieles (Figure 1) Both types of data were recorded with a snow streamer (i.e., geophinies towish on a cable across the snow surface), and the data stow the primary reflection from the ice-water interface, its multiples, and the reflections from and within the seafloor. The explosive source is clearly nets in higher bequencies up to 300 hertz), while the energy in the vibroses record is thinled to the sweep hequencies. The vibrator excites slightly more surface waves than the explosive charge, but the total energy level is higher relative to an explosive charge at 10-meter depth, identifiable reflections are present over a two-way travel time of more than 2 seconds.

With the current vibrosois-spiew streamer etop, seisoric data production is about III kilometers per day for single-fold cower-age, with peak production rates up to 3 kilometers per bour. Optimization should enable a doubling of the production rate to 29 kilo. meters per day even for multifole coverage comparable to oushore vibroses surveys. Sarbace properties disnot impose a proflein, as the vibrator pad (2.5 square meters) generally sank no more than a total of 10–20 continueters in dry snow after three consucu

Future Prospects

A vibrator has the advantage of being a known and repeatable source signal and

Ice Sheets and outpose (8)

Global Shallow-Water Bathymetry From Satellite Ocean Color Data

Knowledge of ocean ballymetry is impor-tion, not only for ravigation but also for selentific studies of the ocean's volume, ecol-ogy, and circulation, all of which are related to Earth's climate. In coastal regions, more over detailed bathymetric maps are crit cat for stoors surge modeling, marine nower plant planning, understanding of erro tem empertivity, coastal management, and cloning analyses. Because ocean areas a commously large and ship surveys have immed coverage, adequate bathymetra, data are still facking throughout the global

scan. Saietite affinetry can produce reasonable estimates of bathymetry for the deep-ocean (Sandwell et al., 2001, 2006). but the spatial resolution is very coarse (sti-9 kilo-meters) and can be highly maccinate in shallow waters, where gravitational effects are small. For example, depths retrieved them the widely used ETL#52 bathconetry database the National Geophysical Data Center's Estimate global reflet data, http:// www.ngdc.noan.gov/mgg/theis/filmgg01 .html) for the Cheat Bahama Baok (Figare lat are seriously interior when companed with stop surveys [Dicessen et al., 2009] (see Figure III). No statistical corre lation was found between the jwo hathym city measurements, and the root-mean-square error of ED PO2 harbymetry was as high as 208 moters. Yet determining a highersmatial resolution by a . IffDonester bathymetry of this region with ship surveys would require about Lyears of nonstep

Clearly, alternative methods are needed his estimating bathymetry in shallow crastal regions. A rapid and relatively robust nethod may be found through a new way of looking at satelflie measurements of occacolor. This takes advantage of the fact that photons folling the shallow ocean bottom and reflecting back to the surface mostify

Repriering Depth From Analyzing Special Data

It is well known that me. water color could help define traffymetry in shallow regions [Letenga, 1981, Polevii et al. 1970). Earlier methods to estimate hathyme using Editor members to estimate narrogen-try from sectan color, however, were finded to approxiches [Lyzenga, 1981, Polevice al., 1970, Philipa, 1989] that require a few known depths in develop an empire at relationship. which then allows researchers in convert multiband-color images to a bathymetri map. The resulting empirical relationships are generally sensor and site specific [Dier ssen et al. 2003; Stompf et al. 2003) and not transferable to other mages or areas Further, the approach is not applicable for regions difficult to reach, doe to lack of in

overcome such a humation, a physics hased approach called reperspectful opti-mization process exemplar (10 PE), has been developed [Lee evin., 1909]. Basically the spectral reflectance (R., the sation water-leaving radiance to downwelling finalliance litting the sea surface) is wool-cled as a function of two independent vari ables that include bothom depth. In a lash an similar is office spectral infinitelline schemes by a Double and Fischer, 1994; Khanaiski et al. 2007 Brando et al. 2008. HOPE derives bottom double by iteratively varying the rables of the bre unknowns until the modeled $\mathcal{B}_{\mathbf{R}}$ best quarefies the

Unlike the emporal approaches used for removing depth from water color (fireinga, 1981; Stomplet at 2003), the only required inputs for 1932; are the spectral reflectance data obtained from a remote sensor, thus eliminating the used for image-specific or region-specific algo-

Bathymetry and misse 180

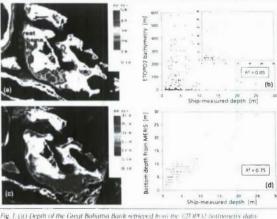


Fig. 1, (a) Depth of the Great Bohama Bank retrieved from the LTOPOA Southwards dambase (b) Seatemphs behaved in silid depth and ETDPOA bath owners of nonthing beautions (finest shous ETOPOA) bathsmers under 60 meters) (a) Boham depth deviced by an Mechani-Besolution hunging Spectrometer (MERIS) measurements (14 Lecenter 2004) by the hypersection of minimum process exemples (40 HFF) approach (14) date Figure 15 a security behaven in silid depth and MERIS depths manifold to nearest integer a crustal ETOPOA formation of the depth and MERIS depths manifold to nearest integer a crustal ETOPOA formation (6) a special set date points (2014) at the depth of No. The coefficient of the depth and the points (2811 in the plan No. The coefficient of the returns to and to Black pixels represent land or deep reades.



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Ice Sheets

also of having feduced logistics custs, higher production rates, and less impact on the environment than explosives. Further invesations should address appropriate selection of vibrator size (commercially avail able vilindors range from 50 kdograms to more than 10 fons) for a trade-off between osolution and penetration depth depend-ing on target objectives and the applicabil ity of vibrator types circlining shear or pressure waves; to suphisticated analysis methods such as amplitude variation with off-set. Logistical limitations require improved implementations such as mounting a vibra for directly our a sleet (instead of our a truck on skiss and modular systems for deplos ment with smaller airplanes.

The vilmoseis-snow streamer configura-tion used presents a fool suitable for traserses of several funding kdometers and thus for target-oriented surveys for specific objectives such as (1) exploring the sub-ice sediment structure suitable for same pling by scientific drilling and analysis for climate information, (2) investigating the physical properties of the ice bedrock inter-like; (3) exploring grounding line processes like internal basal ice structures and water-routing systems. (A) conducting surveys of subglacian axe settings, especially water depth and sediment adormation; (5) complementing radar to exploring the physical properties of the lower part of the ice st and ito typic pogether offshore and oushore seismic data for geological interpretations.

Photos of the vibrator leack and the moasurement schip are available in the online standement to this Envisore office //www arguing/ens_elec/1

Acknowlechments

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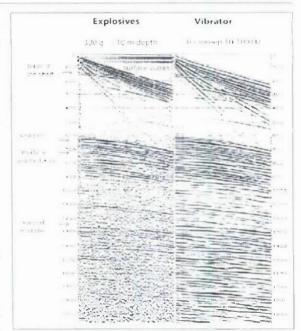


Fig. 1. Comparison of shot gathers sampled at Londose and whereast Signals recorded on iol graphone channels need a distance of 725 moves along the streamer from the explosives some care shown at left, and signals from the voluntor some care shown at light Vertical are indicate hissions travel time in milliserands. The origin of waveril reflection signals is nutround.

Westing delicers for their advice on visosets electronics. Without this support the measurements would not have been possible

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Bathymetry

Application of the New Method

The HEPE method was applied to recent color images of the Great Bahama Bank collected by the Medium-Resolution Imaging Spectrometer (MERIS) operated by the European Space Agency (ESA). The data collected 14 December 2004 by MERIS were locitiv bit IPE to derive properties of the water column and frottom. The derived hottom depth uno tidal correction is pre-sented in Figure 1ct shows a range of identi-1-th meters across the man portions of the banks and a maximum depth of about diffractors at the family entres-

MERES (ferror) depths were compared with strip surveys [Divesser et al., 2009] and it was found that the two data sets were highly statistically contributed, with a continuous square error of MERIS-derived hathymotry of about 3.1 meters (Figure 1d). Note that the errors lactor in the ambiguity that results from differences in the spathat scale of the relative measurements (200) motors for MERIS and +10 motors for ships not the spanial belevogeneity to baltismetry num those scales

Results from querier MERIS incasurement (6 September 2008) show similar accuracy (see Figure 1d), indicating that this approach is reliast and repeatable. Although the error of around 2 nates cardious against the use of these data for navigation, the retrieved Earthymetry is substantially more retained than that presented in ETi Pri 2

Torograph Mone Account Childrell Assassiment of Shallow Wellers

anse polarcoloting sersors like MERIS and Moderate Resolution Imaging Spectro-nationneter (MODS) make measurements giobally and near daily with a spatial near lation of francing is of meters. The proof of concept seen through comparing remote

sensing retrievals with ship surveys around the Great Bahama Bank demonstrates the great potential in deriving global, higher resolution, shallow-water hadrometry from seem color satelifies. Such retrievals can complement information gained from soveys and altometry results. Merging such data products with other bathymetry sources will provide imprecedentedly valuable into malion to scientists, common fall entities esistal mittagers, and decision makers To reach this highly desired real, however would require deslicated efforts to improve and mature algorithms for processing upocally stallow waters from current and fidure became color satellite measurements.

Achimical Stationing

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